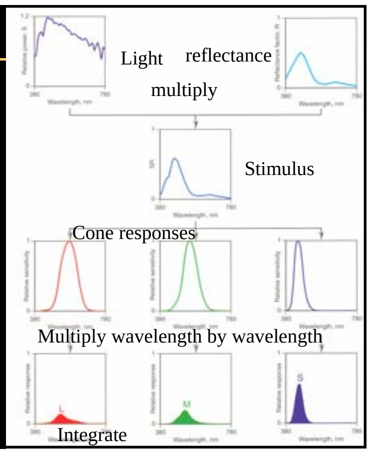
Color

Last time?

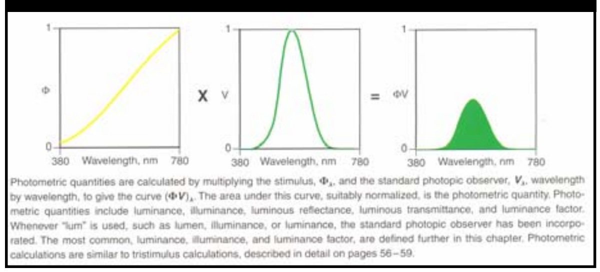
Big picture

- It's all linear!
- But non-orthogonal bases
- Metamers: look the same, different spectrum



CIE

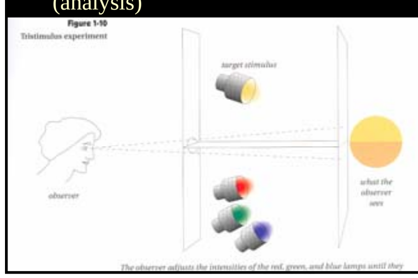
- First in charge of measuring brightness for different light chromaticities
- Predict brightness of arbitrary spectrum (linearity)



Questions?

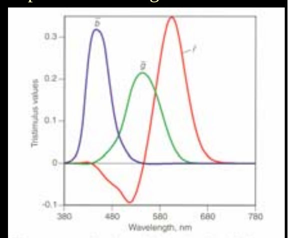
CIE color matching: same for color

- Primaries (synthesis) at 435.8, 546.1 and 700
  - Chosen for robust reproduction, good separation in red-green
- Measure matching curves as function of wavelength (analysis)



CIE color matching

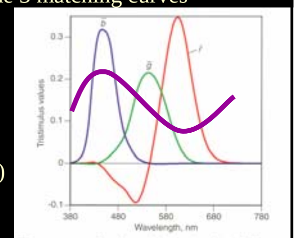
- Primaries (synthesis) at 435.8, 546.1 and 700
  - For robust reproduction, good separation in red-green
- Measure matching curves as function of wavelength (analysis)
- Note that the primaries (monochromatic 435.8, 546.1 and 700nm) are not the same as the matching curve!!!)



These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm

CIE color matching: what does it mean?

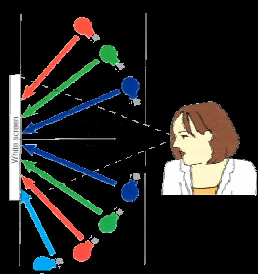
- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)
- However, note that one of the responses could be negative



These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm

Color Matching Problem

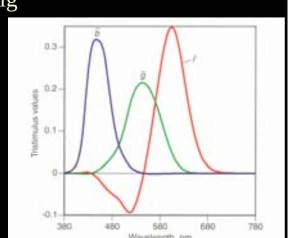
- Some colors cannot be produced using only positively weighted primaries
- Solution: add light on the other side!



Questions?

CIE color matching

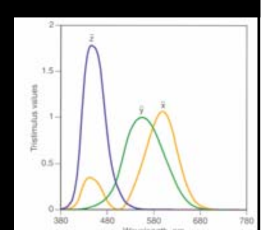
- Problem with these curves:
  - Negative values (was a big deal to implement in a measurement hardware)
  - No direct notion of brightness
- Hence the definition of a new standard



These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm

CIE XYZ

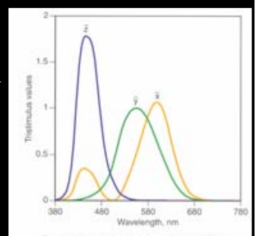
- The most widely recognized color space
- New set of measurement, some linear transformation
- Y corresponds to brightness (1924 CIE standard photometric observer)
- No negative value of matching curve
- But no physically-realizable primary (negative values in primary rather than in matching curve)



The 1931 standard observer, as it is usually shown.

CIE XYZ

- The most widely recognized color space
- A number of the motivations are historical
- Now we're stuck with it ;-(
- But remember, it is always good to agree on a standard
- Although, well, there are two versions of CIE XYZ (1931 and 1964)
- We'll ignore this!



The 1931 standard observer, as it is usually shown.

CIE color space

- Can think of *X*, *Y*, *Z* as coordinates
- Linear transform from typical RGB or LMS
- Always positive (because physical spectrum is positive and matching curves are positives)
- Note that many points in *XYZ* do not correspond to visible colors!

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

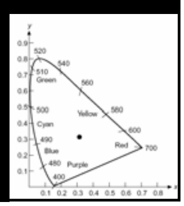
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Chromaticity diagrams

- 3D space are tough to visualize
- Often cares about chrominance, not luminance
- Hence a 2D chromaticity diagram:
  - normalize against $X+Y+Z$:

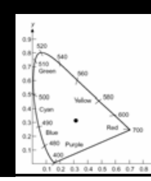
$$x = \frac{X}{X+Y+Z};\quad y = \frac{Y}{X+Y+Z};\quad z = \frac{Z}{X+Y+Z}$$

  - Perspective projection to plane X+Y+Z=1



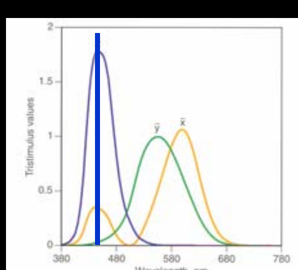
Chromaticity diagrams

- Chromaticity diagram:
  - normalize against $X+Y+Z$:
  - Visualize x and y
  - z easy to deduce: z=1-x-y
- To get full color, usually specify x, y and Y
  - because Y is brightness
  - X= xY/y; Z=(1.0-x-y) Y/y
- Why not normalize against Y?
  - Not clear!

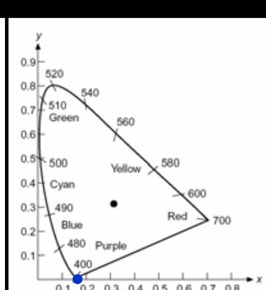


Pure wavelength in chromaticity diagram

- Blue: big value of Z, therefore x and y small

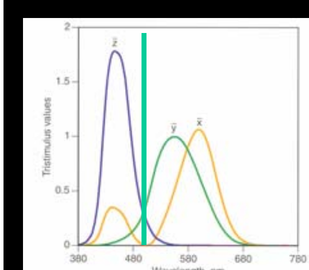


The 1931 standard observer, as it is usually shown.

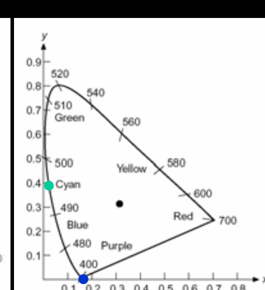


Pure wavelength in chromaticity diagram

- Then y increases

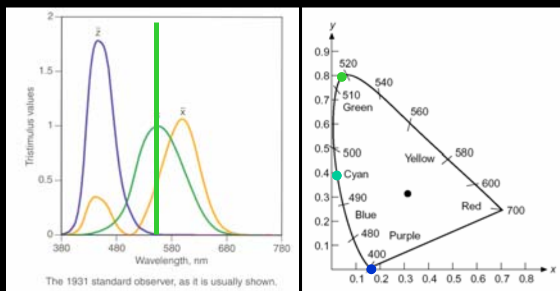


The 1931 standard observer, as it is usually shown.



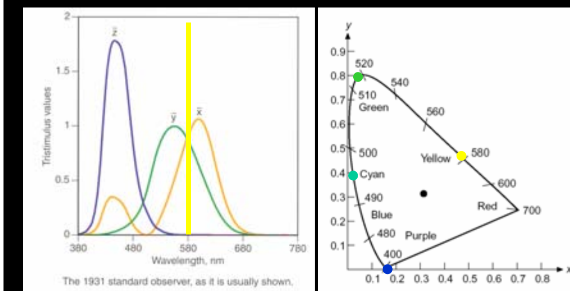
Pure wavelength in chromaticity diagram

- Green: y is big



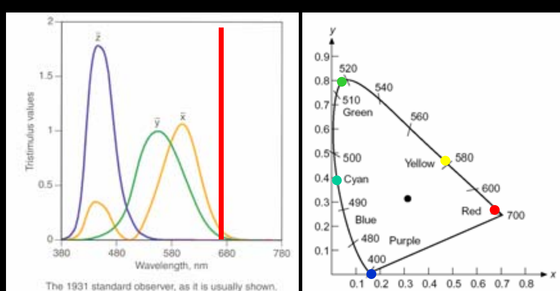
Pure wavelength in chromaticity diagram

- Yellow: x & y are equal



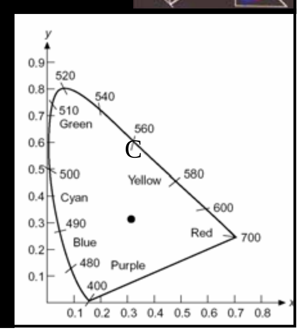
Pure wavelength in chromaticity diagram

- Red: big x, but y is not null



CIE chromaticity diagram

- Spectrally pure colors lie along boundary
- Weird shape comes from shape of matching curves and restriction to positive stimuli
- Note that some hues do not correspond to a pure spectrum (purple-violet)
- Standard white light (approximates sunlight) at **C**



XYZ vs. RGB

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- Linear transform
- XYZ is rarely used for storage
- There are tons of flavors of RGB
  - sRGB, Adobe RGB
  - Different matrices!
- XYZ is more standardized
- XYZ can reproduce all colors with positive values
- XYZ is not realizable physically !!
  - What happens if you go "off" the diagram
  - In fact, the orthogonal (synthesis) basis of XYZ requires negative values.

In summary

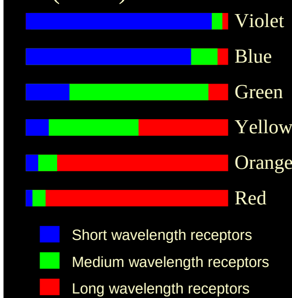
- It's all about linear algebra
  - Projection from infinite-dimensional spectrum to a 3D response
  - Then any space based on color matching and metamerism can be converted by 3x3 matrix
- Complicated because
  - Projection from infinite-dimensional space
  - Non-orthogonal basis (cone responses overlap)
  - No negative light

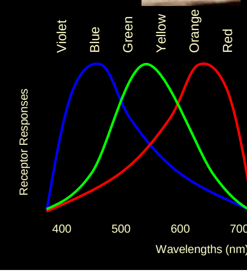
Questions?

Lippman spectral color reproduction

Remember von Helmholtz

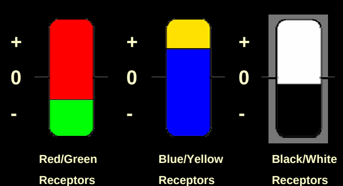
- Colors as relative responses (ratios)





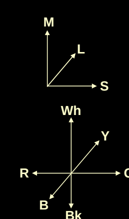
Hering 1874: Opponent Colors

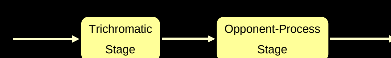
- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena



Dual Process Theory

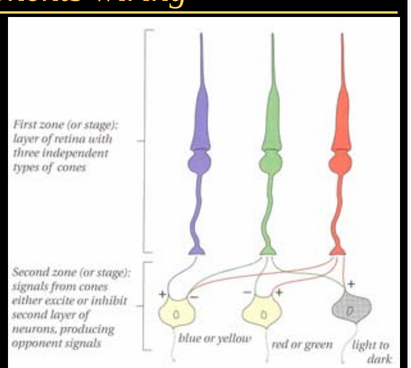
- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green



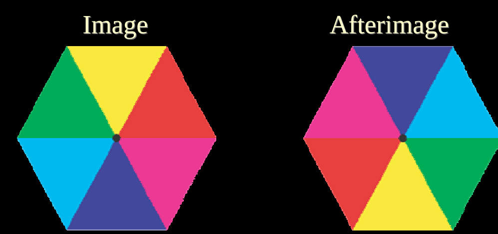


Color opponents wiring

- Sums for brightness
- Differences for color opponents
- At the end, it's just a 3x3 matrix compared to LMS

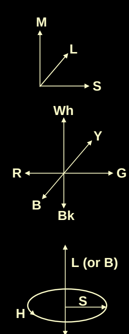


Opponent Colors



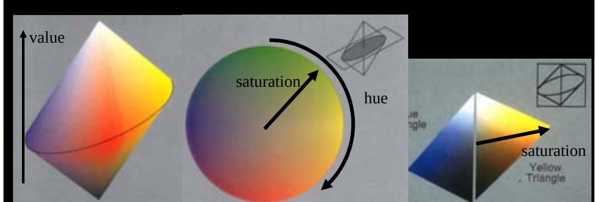
Color reparameterization

- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green
- A later stage may reparameterize:
  - Brightness or Luminance or Value
  - Hue
  - Saturation



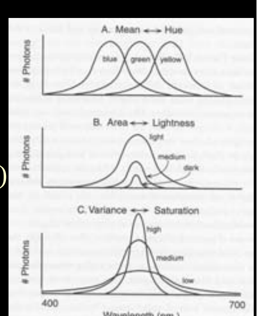
Hue Saturation Value

- Value: from black to white
- Hue: dominant color (red, orange, etc)
- Saturation: from gray to vivid color
- HSV double cone



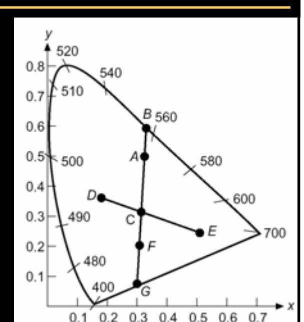
Hue Saturation Value

- One interpretation in spectrum space
- Not the only one because of metamerism
- Dominant wavelength (hue)
- Intensity
- Purity (saturation)



CIE color space

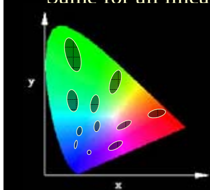
- Hue, saturation and value of a color A
- Use white point C
- Hue: project A onto spectrum curve
- Saturation: ~ distance from C
- Value: Y



Questions?

Perceptual color difference

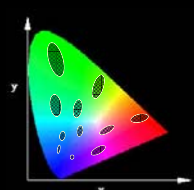
- In color space CIE-XYZ, the perceived distance between colors is not equal everywhere
- Can be represented by ellipses of perceived differences (set of colors that look no more different than a given threshold)
- Measured by MacAdam
- Same for all linear color spaces (RBG, LMS, etc.)

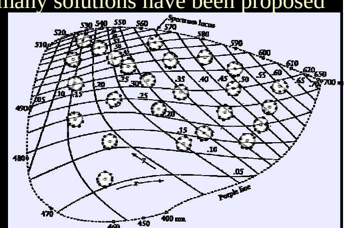


Source: [Wyszecki and Stiles '82]

Perceptually Uniform Space: MacAdam

- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors
- MacAdam ellipses (areas of unperceivable differences) become circles
- Non-linear mapping, many solutions have been proposed





Source: [Wyszecki and Stiles '82]

CIELAB (a.k.a. CIE L*a*b*)

- The reference perceptually uniform color space
- L: lightness
- a and b: color opponents
- X_0, Y_0, and Z_0 are used to color-balance: they're the color of the reference white

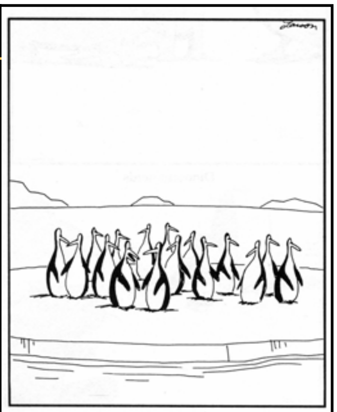
$$L = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

Source: [Wyszecki and Stiles '82]

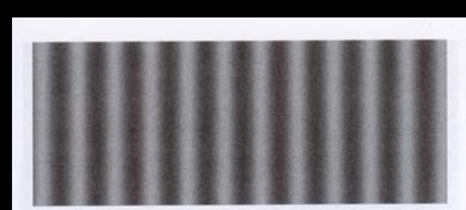
Question?



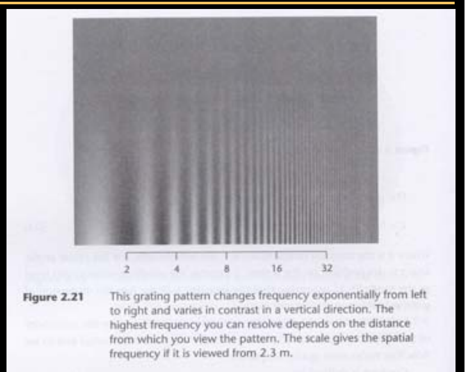
"Well, that's an interesting bit of trivia — I guess I *do* only dream in black and white."

Contrast Sensitivity

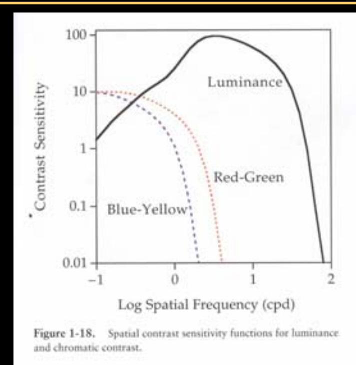
- Sine Wave grating
- What contrast is necessary to make the grating visible?



Contrast Sensitivity Function (CSF)

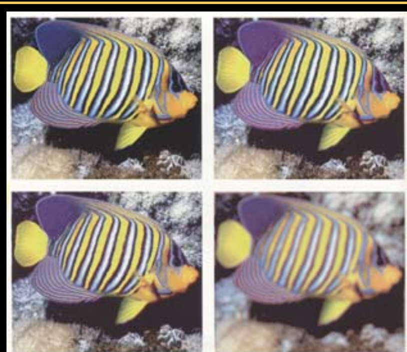


Contrast Sensitivity Function (CSF)



Opponents and image compression

- JPG, MPG
- Color opponents instead of RGB
- Compress color more than luminance



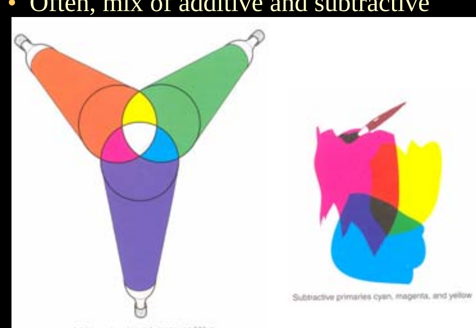
JPEG Compression

- Perform DCT to work in frequency space
  - Local DCT, 8x8 blocks
- Use CSF for quantization
  (more bits for sensitivity with more contrast)
- Other usual coding tricks

Questions?

Color synthesis: additive vs. subtractive

- Often, mix of additive and subtractive



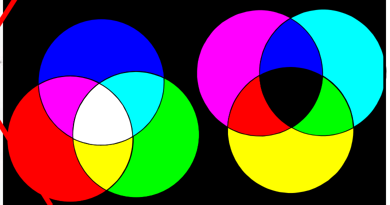
*Color synthesis: a **wrong** example*

Additive

red, green, blue

Subtractive

cyan, magenta, yellow

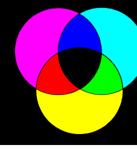


WRONG

RIGHT

Device Color Models (Subtractive)

- Start with white, remove energy (e.g., w/ ink, filters)
- Example: CMY color printer
  - Cyan ink absorbs red light
  - Magenta ink absorbs green light
  - Yellow ink absorbs blue light
  - C+M+Y absorbs all light: Black!
- RGB => CMY conversion
- Some digital cameras use CMY



$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

CMYK

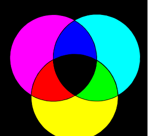
CMY model plus black ink (K)

Saves ink

Higher-quality black

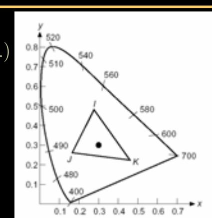
Increases gamut

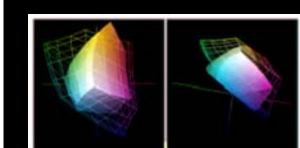
Conversion not completely trivial



Gamut

- Every device with three primaries can produce only colors inside some (approx.) triangle
  - Convexity!
- This set is called a color gamut
  - (Why can't RGB give all visible colors?)
- Usually, nonlinearities warp the triangle
  - Also, gamut varies with luminance



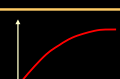


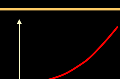
Gamut of printer and CRT visualized in Lab

Questions?

The infamous gamma curve

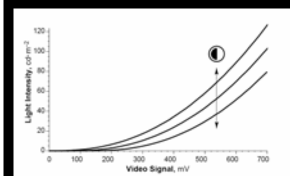
- A gamma curve $x \to x^{\gamma}$ is used for many reasons:
  - CRT response
  - Color quantization
  - Perceptual effect
- Sometimes with $\gamma > 1$, sometimes $\gamma < 1$
- These issues are often oversimplified/confused, including in prominent textbooks
  - i.e. they are explained wrong





Cathode Ray Tube gamma

- The relationship between voltage and light intensity is non linear
- Can be approximated by an exponent 2.5
- Must be inverted to get linear response



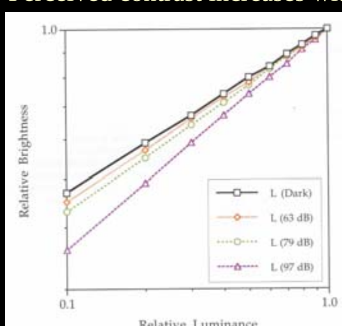
From Ponton’s FAQ
http://www.poynton.com/

Color quantization gamma

- The human visual system is more sensitive to ratios: is a grey twice as bright as another one?
- If we use linear encoding, we have tons of information between 128 and 255, but very little between 1 and 2!
- This is why a non-linear gamma remapping of about 2.0 is applied before encoding
- True also of analog signal to optimize signal-noise ratio
- It is a nice coincidence that this is exactly the inverse of the CRT gamma

Stevens effect

- Perceived contrast increases with luminance



Perceptual effect

- We perceive colors in darker environment less vivid
- Must be compensated by boosting colors

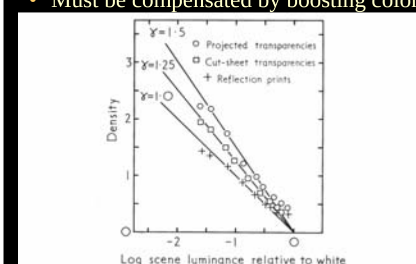


Fig. 6.13. The displayed density of the nine-step grey scale plotted against the log luminances of its steps relative to white. Reflection print systems have a displayed gamma of 1.0, cut-sheet transparency systems a displayed gamma of 1.25, and projected transparency systems a displayed gamma of 1.5.

At the end of the day

- At the camera or encoding level, apply a gamma of around 1/2.2
- The CRT applies a gamma of 2.5
- The residual exponent 2.2/2.5 boosts the colors to compensate for the dark environment
- See
  http://www.poynton.com/GammaFAQ.html
  http://www.poynton.com/notes/color/GammaFQA.html
  http://www.poynton.com/PDFs/Rehabilitation_of_gamma.pdf

Gamma is messy

- Because it’s poorly understood
- Because it’s poorly standardized
  - Half of the images on the net are linear, half are gamma-compressed
- Because it might make your image processing non-linear
  - A weighted average of pixel values is not a linear convolution! Bad for antialiasing
  - But it is often desirable for other image processing, because then it corresponds more to human perception of brightness

Questions?

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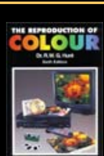

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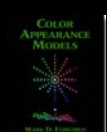

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